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13. ABSTRACT (Maximum 200 words)

Summary of Accomplishments:

The overarching theme of the work originally proposed concerned the development of three-dimensional computational capability enabling the lagrangian simulation of armor penetration. The principal objectives of the work, as stated in the proposal, were:
i) The development of three-dimensional computational capability including adaptive meshing, direct simulation of fracture and fragmentation by cohesive elements, nonsmooth contact and friction.
ii) Verification and validation of the unit algorithms.
iii) The demonstration of the predictive ability of the integrated facility in problems of ballistic penetration of interest to the Army.
All the unit algorithms required to carry out the simulations of interest in three dimensions have been developed and successfully tested. The degree of difficulty involved in the development of these algorithms varies from low (e.g., the extension of the constitutive updates to three dimensions) to exceptional high (most notably, the development of automatic 3D meshing capability for arbitrary domains). Some of the main accomplishments are summarized next.

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Three-Dimensional Modelling and Simulation of Ballistic Impact

Final Report

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Grant Number: DAAH04-96-1-0056

1 Summary of accomplishments

The overarching theme of the work originally proposed concerned the development of three-dimensional computational capability enabling the lagrangian simulation of armor penetration. The principal objectives of the work, as stated in the proposal, were:

i) The development of three-dimensional computational capability including adaptive meshing, direct simulation of fracture and fragmentation by cohesive elements, nonsmooth contact and friction.

ii) Verification and validation of the unit algorithms.

iii) The demonstration of the predictive ability of the integrated facility in problems of ballistic penetration of interest to the Army.

All the unit algorithms required to carry out the simulations of interest in three dimensions have been developed and successfully tested. The degree of difficulty involved in the development of these algorithms varies from low (e. g., the extension of the constitutive updates to three dimensions) to exceptionally high (most notably, the development of automatic 3D meshing capability for arbitrary domains). Some of the main accomplishments are summarized next.

1.1 Automatic 3D meshing

The development of robust three-dimensional triangulation algorithms for arbitrary domains and graded unstructured meshing is one of the focal points of research in computational mechanics and computational geometry at present. This task has

proven the most difficult one of all, closely followed by the nonsmooth contact algorithm. We have developed a reliable advancing-front 3D mesher capable of generating !netnonstructured tetrahedral meshes of complex domains in accordance with a prescribed mesh-density function such as obtained from error estimation. The approach has been described in the article:

> Radovitzky, R. and Ortiz, M. "Tetrahedral mesh generation based on node insertion in crystal lattice arrangements and advancing-front Delaunay triangulation," *Computer Methods in Applied Mechanics and Engineering,* (3-4) 543-569 2000.

1.2 Mesh adaption

The lagrangian simulation of unconstrained plastic deformations requires continuous mesh adaption to eliminate the deformation-induced mesh distorsion. Mesh adaption also serves the purpose of resolving the fine scales in the solution, such as shear bands. For all these reasons, adaptive meshing is a hallmark of a truly advanced simulation facility. We have developed error bounds applicable to strongly nonlinear dynamic problems, a class of problems for which methods of effective error estimation were previously unavailable. We use these error bounds to drive mesh adaption. We have verified that the resulting meshes minimize the solution error for a fixed number of elements and result in optimal convergence. These results have been described in the article:

> Radovitzky, R. and Ortiz, M. "Error estimation and adaptive meshing in strongly nonlinear dynamic problems," *Computer Methods in Applied Mechanics and Engineering,* 172: (1-4) 203-240 APR 16 1999.

As an alternative approach, we have evaluated a mesh-refinement strategy based on Rivara's longest-edge propagation path (LEPP) bisection algorithm. Our strategy for mesh coarsening, or unrefiment, is based the elimination of elements by edge-collapse. The convergence characteristics of the method in the presence of strong elastic singularities have been tested numerically. An application to the three-dimensional simulation of adiabatic shear bands in dynamically loaded tantalum has also been developed which demonstrates the robustness and versatility of the method. These results have been described in the article:

> Molinari, J. F. and Ortiz, M. "Three-Dimensional Adaptive Meshing by Subdivision and Edge-Collapse in Finite-Deformation Dynamic-Plasticity Problems with Application to Adiabatic Shear Banding," *Computer Methods in Applied Mechanics and Engineering,* in press.

1.3 Fracture and fragmentation

We have successfully extended to three dimensions our cohesive element capability. Our cohesive elements are equipped with full finite-deformation kinematics and a

variety of irreversible cohesive laws of our own design. The approach is described in the articles:

> Ortiz, M. and Pandolfi, A., " Finite-Deformation Irreversible Cohesive Elements for Three-Dimensional Crack-Propagation Analysis," *International Journal of Numerical Methods in Engineering,* 44: (9) 1267-1282 MAR 30 1999.
>
> Pandolfi, A. and Ortiz, M., "Solid Modeling Aspects of Three- Dimensional Fragmentation," *Engineering with Computers,* 14: (4) 287-308 1998.

1.4 Nonsmooth fracture

In problems of fragmentation, a common occurrence is that several angular (nonsmooth) fragments come together at a point and undergo complex collision sequences before they eventually scatter. In these situations, normals and gap functions cannot be meaningfully defined, which renders the traditional contact algorithms inapplicable. We have develop a new class of nonsmooth contact algorithms which has proven effective at dealing with the kind of contact configurations just described in three dimensions. The ability to resolve nonsmooth contact configurations in turn enables the direct simulation of fragmentation processes. The nonsmooth contact algorithm is described in the article:

> Kane, C., Repetto, E.A., Ortiz, M. and Marsden, J. E., "Finite Element Analysis of Nonsmooth Contact, *Computer Methods in Applied Mechanics and Engineering,* 180: (1-2) 1-26 NOV 15 1999.

1.5 Validation tests

We have validated the new three-dimensional capability by means of extensive comparisons with archival data. Some of the relevant work in this direction is the following:

1.5.1 Dynamic drop-weight test

As a first validation case, we have taken the dynamic drop-weight test as a convenient basis for assessing the predictive ability of cohesive models in applications involving dynamic crack growth. The numerical simulations have proven highly predictive of a number of observed features, including: the crack growth initiation time; the trajectory of the propagating crack tip; and the formation of shear lips near the lateral surfaces. The simulations therefore establish the feasibility of using cohesive models of fracture and cohesive elements to predict three-dimensional dynamic crack-growth initiation and propagation.

Pandolfi, A., Guduru, P. R., Ortiz, M. and Rosakis, A. J., "Finite element analysis of experiments of dynamic fracture in C300 steel," *International Journal of Solids and Structures*, 37: (27) 3733-3760 JUL 2000

1.5.2 Ring-expansion tests

A second validation case concerns the expanding ring tests of Grady and Benson (1983). This case tests the predictive ability of cohesive models in situations involving ductile dynamical fracture. Attention has been restricted to 1100-0 aluminum samples. The numerical simulations are highly predictive of a number of observed features, including: the number of dominant and arrested necks; the fragmentation patterns; the dependence of the number of fragments and the fracture strain on the expansion speed; and the distribution of fragment sizes at fixed expansion speed.

Pandolfi, A. and Krysl, P. and Ortiz, M., "Finite element simulation of ring expansion and fragmentation," *International Journal of Fracture*, 95: (1-4) 279-297 1999.

1.5.3 Dynamic Brazilian test

A third validation case has been concerned with the dynamic response of concrete in tension. The particular configuration contemplated in the study is the Brazilian cylinder test performed in a Hopkinson bar. The simulations give accurate transmitted loads over a range of strain rates, which attests to the fidelity of the model where rate effects are concerned. The model also predicts key features of the fracture pattern such as the primary lens-shaped cracks parallel to the load plane, as well as the secondary profuse cracking near the supports. The primary cracks are predicted to be nucleated at the center of the circular bases of the cylinder and to subsequently propagate towards the interior, in accordance with experimental observations. The primary and secondary cracks are responsible for two peaks in the load history, also in keeping with experiment. These results validate the theory as it bears on mixed-mode fracture and fragmentation processes in concrete at any strain-rate.

Ruiz, G., Ortiz, M. and Pandolfi, A., "Three-Dimensional Finite-Element Simulation of the Dynamic Brazilian Tests on Concrete Cylinders," *International Journal for Numerical Methods in Engineering*, 48: (7) 963-994 JUL 10 2000.

1.5.4 Solid-Particle Erosion of Metallic Targets

We have also performed detailed finite element simulations of impact of metallic plates by spherical particles over a range of impact angles and speeds with a view to developing insight into the fundamental mechanisms underlying solid-particle erosion. The particular experimental configuration and data set which we analyze corresponds to

the experiments of Hutchings (1976), consisting of high-strength steel spherical particles striking mild-steel target plates. The material description used in calculations includes finite deformations, strain hardening, thermal softening, rate sensitivity, frictional contact, heat generation due to plastic working and friction, dynamics and heat conduction. The analysis reveals insights into the relative roles played by plastic flow, friction and adiabatic shearing over the full range of impact angles from glancing to normal impact; and over impact velocities ranging from 141 to 2000 m/s.

Molinari, J. F., and Ortiz, M., "A Study of Solid-Particle Erosion of Metallic Targets," *International Journal of Impact Engineering*, submitted for publication.